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EFFECT OF VARIABLE STATOR AREA ON PERFORMANCE OF A SINGLE-STAGE TURBINE SUITABLE FOR AIR COOLING

VI. Turbine Performance With 70-Percent Design Stator Area

by Harold J. Schum, Edward M. Szanca, and Herman W. Prust, Jr.

Lewis Research Center
Cleveland, Ohio

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ABSTRACT

The performance of this turbine is compared with those obtained for the design and the 130-percent design-stator-area turbines. Whereas the design turbine yielded an efficiency of 0.923 at its equivalent design operating condition, the closed turbine produced an efficiency of only 0.840 at the same operating point. This compares with 0.897 for the open turbine. The large loss of efficiency for the closed turbine is attributed mainly to the high velocities at the stator exit, incidence to the rotor, and substantially reduced reaction across the rotor.

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SUMMARY

The performance changes resulting from adjusting the stator flow area of an experimental 30-inch (0.762-m) tip-diameter single-stage turbine are being investigated. The performance of this turbine, when tested with both design and 130-percent design stator areas, has been reported. This report presents the performance of this same turbine when equipped with a stator having 70-percent of design area. The area changes were effected by reorienting the blades to the stagger angle required to provide the desired flow area. The identical rotor was used for each investigation.

When results of the three turbine configurations were compared at an operating point corresponding to equivalent design speed and an equivalent specific work output of 17.00 Btu per pound (39 572 J/kg), the closed turbine yielded an efficiency of 0.840. This efficiency was considerably lower than the 0.923 obtained for the design turbine and the 0.897 obtained for the open turbine. An estimate of the losses through the closed turbine at this condition indicated a 3-percent stator loss, a 2-percent loss due to rotor incidence, and an 11-percent rotor-loss. The rotor losses were a result of the high velocities out of the stator with a substantially reduced reaction across the rotor.

INTRODUCTION

The NASA Lewis Research Center is conducting a test program on a single-stage 30-inch (0.762-m) tip-diameter, cold-air turbine with blading typical of that used in advanced engines. This blading is characterized by blunt leading and trailing edges and thick profiles, as dictated from air-cooling considerations. Furthermore, the turbine was designed with low blade solidities, thereby reducing the number of blades to be cooled. The design technique and the resultant turbine blade shapes are presented in reference 1. When this turbine was tested (ref. 2), it was found that the turbine efficiency was not adversely affected by the aerodynamic compromises made in the design of the blades. An efficiency of 0.923 was obtained at equivalent design speed and work output.

The research program on this turbine was extended to investigate the effect of variable stator area on turbine performance. The use of variable turbine geometry is one method considered (e.g., ref. 3) for permitting the engine to operate efficiently at more than one flight condition. Variable-stator area would provide a varying flow rate for a given turbine pressure ratio. However, changes in stator area correspond to off-design conditions of turbine operation. And it is obviously desirable to maintain high turbine efficiency at these off-design operating conditions.

Accordingly, Lewis had two additional stators fabricated. One had a flow area 30 percent greater than design; the other 30 percent less than design. These area changes were effected by changing the stagger angle of the design blades. Each stator was installed in the test facility and tested with the same rotor as that used for the design turbine investigation (ref. 2). Results of the investigation with the increased area stator (ref. 4) indicated a decrease in efficiency of 0.026 when compared at the design turbine equivalent speed and work output.

This report presents the results of the experimental investigation made to determine the effect of the decreased stator area on overall turbine stage performance. This turbine was tested over a range of speed and pressure ratio. Turbine-inlet pressure was maintained at 30 inches of mercury absolute (1.0159×10^5 N/m^2). Inlet air temperature from the laboratory combustion air system was about 550° R (306 K). Speed was varied from 40 to 110 percent equivalent design speed in 10-percent increments. Equivalent mass flow, equivalent torque, and rotor-exit flow angle data are presented. Also included is a performance map, with turbine efficiency, based on the total-pressure ratio, used to indicate turbine performance. The results are compared with those previously obtained for the two turbines wherein the design- and the 130-percent design area stators were incorporated (refs. 2 and 4, respectively).

For convenience in the ensuing discussion, the subject turbine, equipped with the stator having a flow area 70-percent that of design, will be termed the closed turbine; the turbine with the 130-percent area stator will be called the open turbine; and the turbine with the design area stator will be referred to as the design turbine.

SYMBOLS

h specific enthalpy, Btu/lb; J/kg

N rotational speed, rpm

p absolute pressure, lb/ft^2; N/m^2

U blade velocity, ft/sec; m/sec

V absolute gas velocity, ft/sec; m/sec

W gas velocity relative to rotor blade, ft/sec; m/sec

w mass flow rate, lb/sec; kg/sec

α absolute flow angle, measured from axial, positive in direction of rotor rotation, deg

α_s blade stagger angle, deg

β relative flow angle measured from axial direction, deg

δ ratio of inlet pressure to U. S. standard sea-level pressure

η efficiency based on total pressure ratio

θ_{cr} squared ratio of critical velocity at turbine inlet to critical velocity of U. S. standard sea-level air

τ torque, ft-lb; N-m

Subscripts:

cr condition at Mach 1

h turbine hub section

i measuring station at stator throat

t turbine tip section

u tangential component

x axial component

0 measuring station at turbine inlet

1 measuring station at stator outlet

2 measuring station at rotor outlet

Superscripts:

' total state

APPARATUS AND INSTRUMENTATION

The design of the research turbine is presented in reference 1, along with blading coordinates. For the investigation reported herein, the stator blades were reoriented to

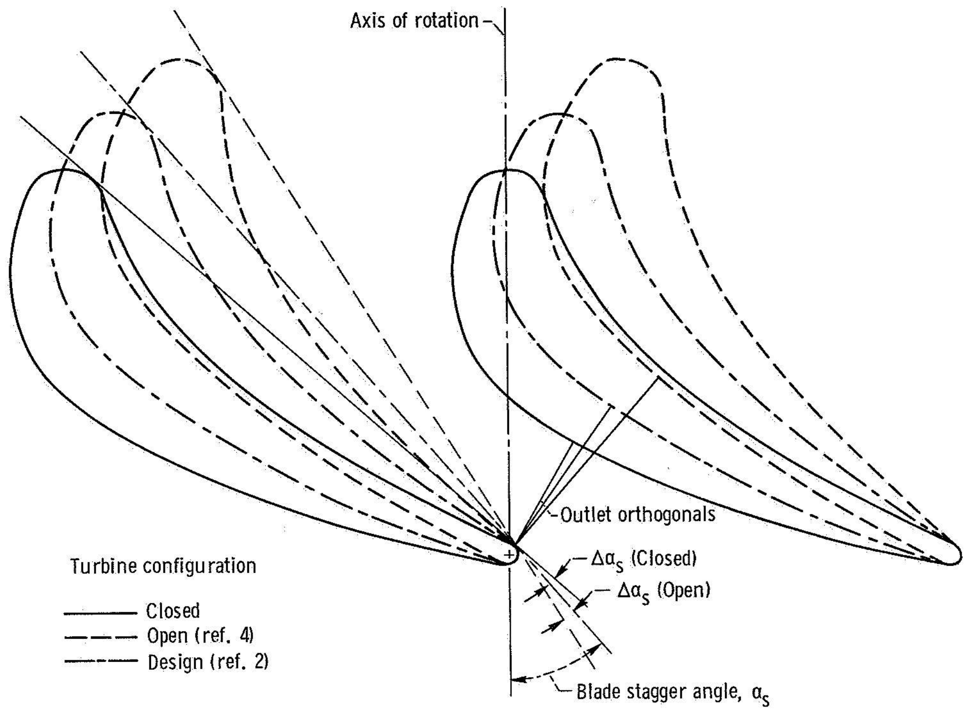

Figure 1. - Comparison of stator blade mean-section orientation for three turbines.

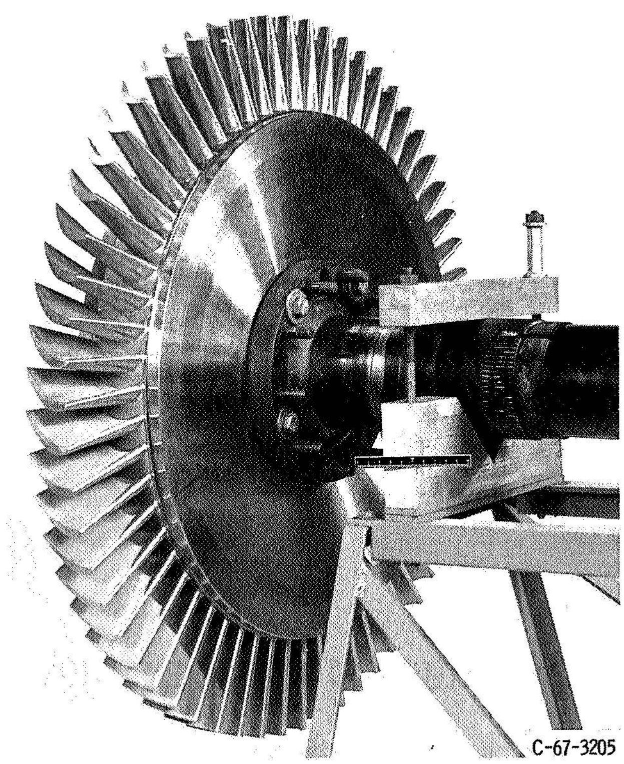

Figure 2. - Turbine rotor.

the stagger angle α_s required to decrease the mean-section channel outlet orthogonal length 30 percent less than that for the design stator. The resultant stator-blade stagger angle change for the closed-turbine investigation amounted to 7.79° toward the tangential. And it compares with an 8.44° change toward the axial for the open-turbine investigation of reference 4. These changes are shown in figure 1. The channel outlet orthogonal length changes can also be noted.

The rotor was the same as that used in the design- and the open-turbine performance evaluations (refs. 2 and 4, respectively). A photo of the rotor is shown in figure 2.

The test facility for the closed-turbine investigation was the same as that for the design- and the open-turbine investigations. A photograph of the experimental facility is shown in figure 3. The closed stator-blade row is shown installed in the facility and with

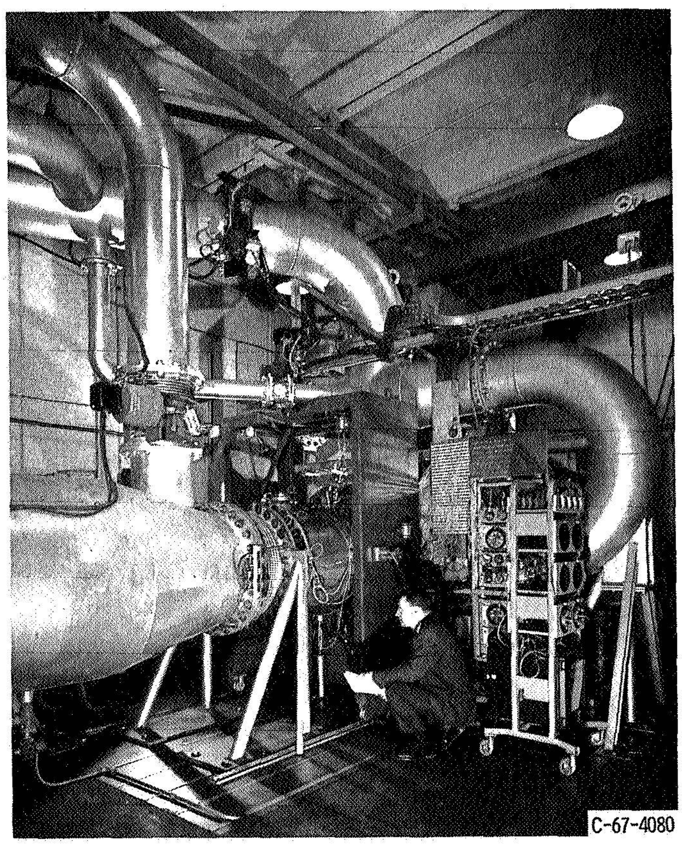

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Figure 3. - Test facility.

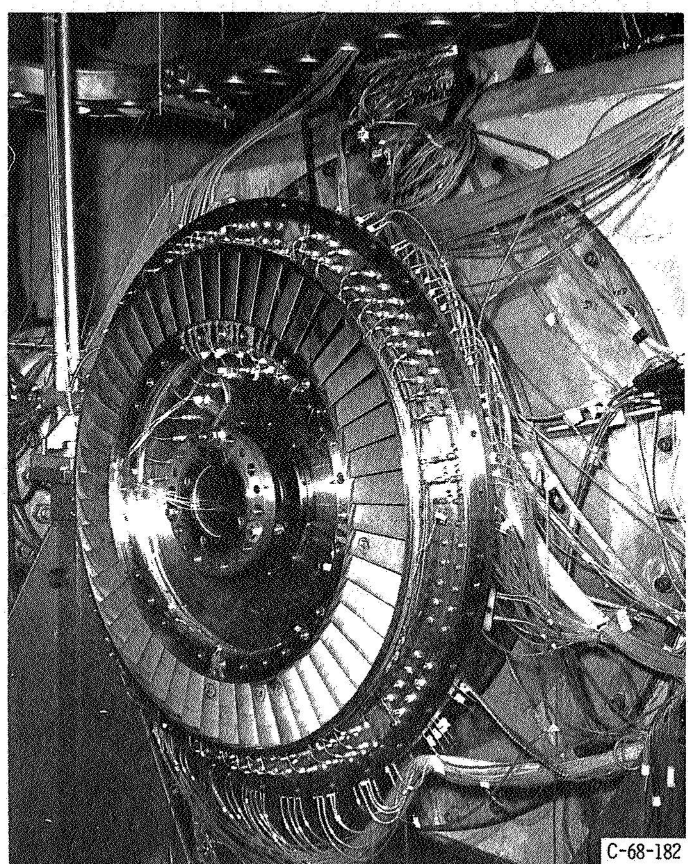


Figure 4. - Stator assembly.

the rotor removed (fig. 4). A schematic diagram of the overall turbine setup is shown in figure 5.

The instrumentation required to determine overall turbine performance of the closed turbine was the same as that described in references 2 and 4. Measurements were made at the axial locations shown in the inset of figure 5. Axial-circumferential locations of total pressure probes, wall static-pressure taps, and angle sensing probes are depicted in figure 6. It is noted that wall static-pressure taps were provided in the plane of the exit orthogonals (measuring station i), midway between adjacent blades, on both the inner and outer walls.

Air mass flow was metered using a calibrated Dall tube located in the combustion-air supply line. Valves in this line were used to throttle the pressure to the desired turbine-inlet pressure. After passing through the turbine, the air was discharged to the altitude exhaust system. Butterfly throttle valves were used to set the desired pressure at the outlet of the turbine.

Rotative speed was measured with an electronic counter in conjunction with a mag-

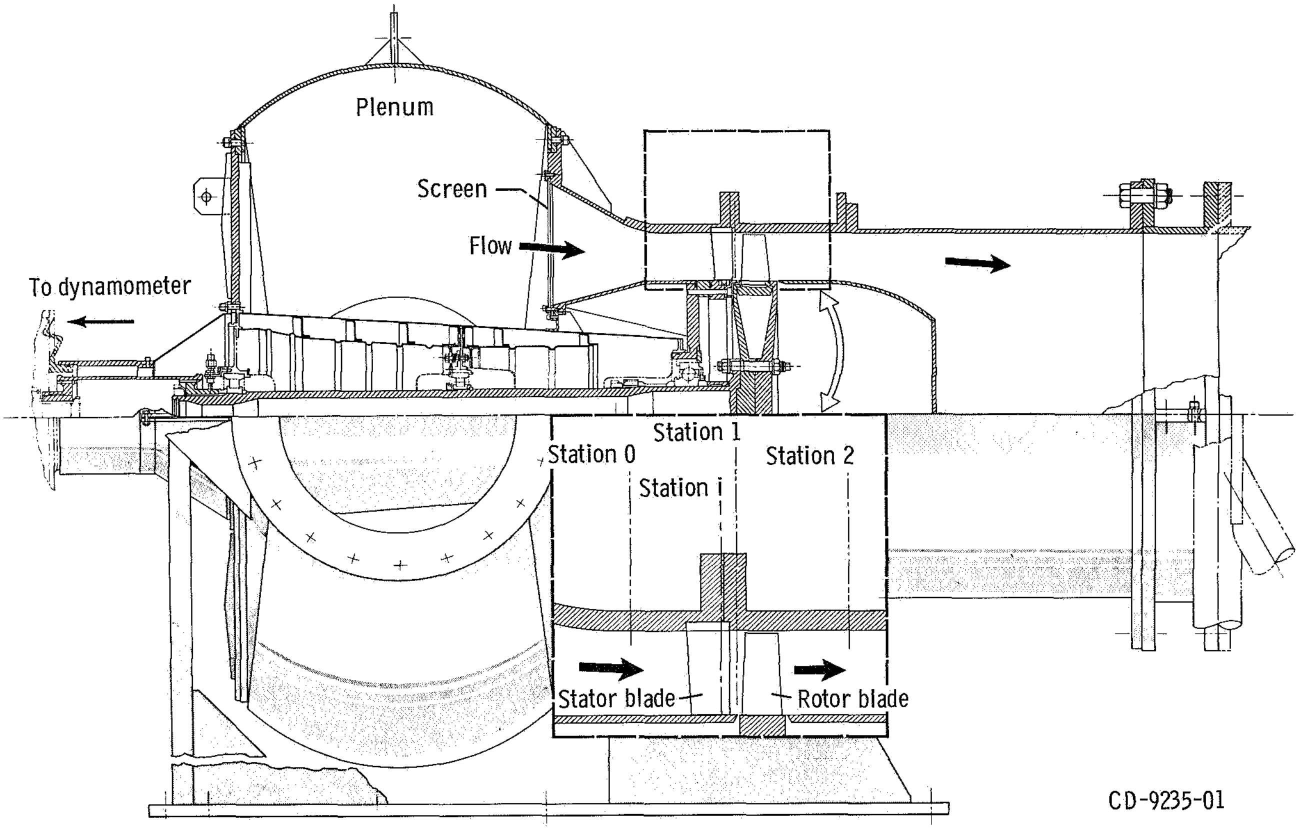


Figure 5. - Schematic diagram of turbine test section.

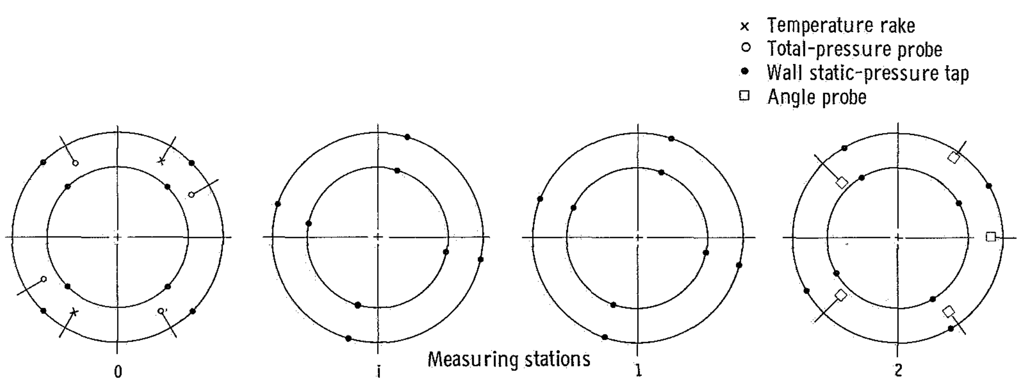


Figure 6. - Schematic diagram of turbine instrumentation, viewed upstream.

netic pickup and a gear fastened to the turbine shaft. Turbine torque output was measured on the dynamometer stator with a strain-gage load cell in conjunction with a digital voltmeter.

PROCEDURE

The turbine was rated on an inlet total to outlet total pressure ratio p_0'/p_2'. Both total pressures were calculated in the manner described in reference 2. The inlet total pressure was maintained at 30 inches of mercury absolute (1.0159×10^5 N/m^2) for all tests. Inlet air temperature from the laboratory combustion-air system varied from 546° to 558° R (303.8 to 310.0 K). A range of speeds from 40 to 110 percent of the design equivalent speed, in 10 percent increments, was investigated. At each speed, the turbine was operated over a range of total-pressure ratios.

Equivalent mass flow $w\sqrt{\theta_{cr}}/\delta$ and equivalent torque τ/δ data were plotted as functions of total-pressure ratio and equivalent speed $N/\sqrt{\theta_{cr}}$. From these two plots a performance map was constructed in terms of equivalent specific shaft work output $\Delta h/\theta_{cr}$, a mass flow-speed parameter wN/δ, and total-pressure ratio. Superimposed are contours of efficiency η, which are based on the total-pressure ratio.

RESULTS AND DISCUSSION

The results of the closed-turbine experimental investigation are presented in two parts. First, the performance of the turbine is presented in terms of measured values, with a resultant performance map. The second part compares the performance of this turbine, when operated at equivalent design speed, to corresponding results previously obtained from the design turbine and the open turbine. A velocity diagram study was also made at a specific operating point for the three turbines. These comparisons are made to further indicate the effect of variable stator area on turbine performance.

Stage Performance of Closed Turbine

The overall turbine performance is presented in terms of torque and mass-flow characteristics, from which the performance map was evolved. In addition, the variation in static pressure at the various measuring stations is presented. Also, variation in turbine exit flow angle is shown.

Overall turbine performance. - Figure 7 shows the variation of torque as a function

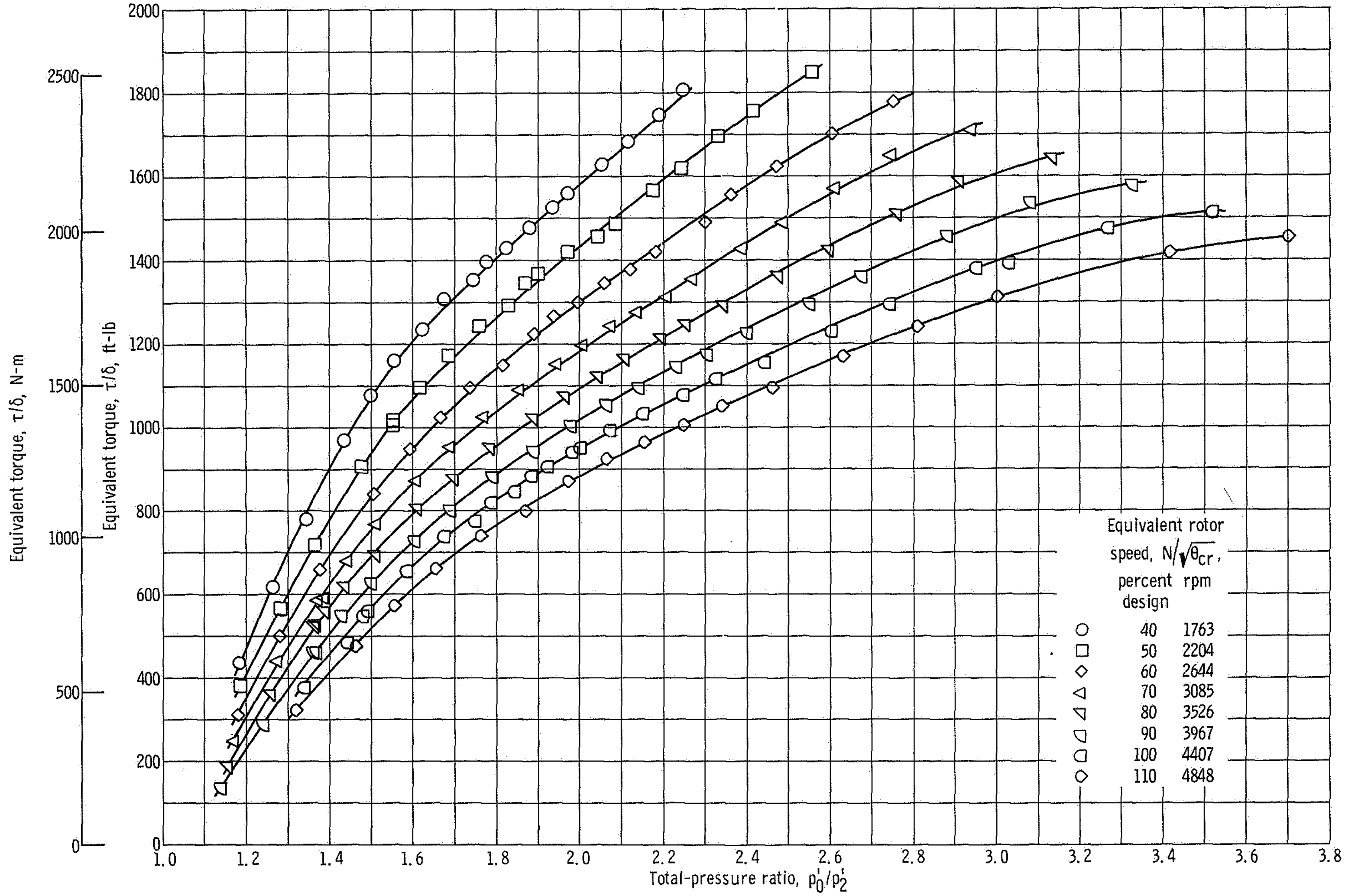


Figure 7. - Variation of equivalent torque with total-pressure ratio for various equivalent rotor speeds.

of total-pressure ratio across the turbine for various rotor speeds. Torque continuously increased with increasing pressure ratio, indicating that limiting loading was not attained over the range of pressure ratios investigated.

The variation of mass flow with total-pressure ratio over the range of rotor speeds investigated is presented in figure 8. The mass flow, for all speeds, increased with increasing pressure ratio until it reached a constant value of 30.71 pounds per second (13.93 kg/sec). This indicates that the stator blade row was choked. This mass flow occurred at a total-pressure ratio of about 2.0 for the 40-percent design speed. And, as the speed was increased to 110-percent design speed, this choking pressure ratio increased to about 2.4.

The performance map (fig. 9) was evolved from the data of figures 7 and 8 by using the procedure outlined in reference 4. Figure 9 shows that a maximum efficiency of slightly over 87 percent was obtained at the 110-percent speed, occurring at a total-pressure ratio around 1.6. The choking mass flow can be noted by the vertical speed lines.

Of interest is the required pressure ratio and efficiency that yielded the design work output of 17.00 Btu per pound (39 572 J/kg) for the design turbine of reference 2. At design speed, this work output is shown by the data symbol on the performance map (fig. 9). Cross-plots of data for the design speed show that this work output occurred at a total-pressure ratio of 1.860. The attendant efficiency was 0.840. From figure 8, the corresponding mass flow was determined to be 30.26 pounds per second (13.73 kg/sec), which is very close to the choking value.

Static-pressure distribution. - The static-pressure distribution through the turbine is shown in figure 10 as a function of total-pressure ratio for the design speed. Wall static-pressure measurements at the hub are presented in figure 10(a); tip measurements are presented in figure 10(b). Choking in a blade row is indicated when the static pressure at the inlet to a blade row remains constant while the static pressure at the outlet of the same blade row continued to decrease as the total-pressure ratio across the turbine is increased. The data shown for the design speed (fig. 10) are typical for all other speeds investigated.

From figure 8, it can be noted that, for the design speed, the stator choked at a total-pressure ratio of about 2.4. Referral to figure 10(a) shows that the stator blade row choked first at the hub at a pressure ratio of about 1.9 and that this blade row choking apparently progressed radially outward with increased pressure ratio until, at a total-pressure ratio of about 2.8, the stator choked at the tip section.

Figure 10(a) also shows that, at the hub, considerable expansion occurred from the stator-blade throats (measuring station i) to the stator outlet (measuring station 1), resulting in supersonic flow. Supersonic velocities were also observed on the blade surfaces at the hub, when the subject closed stator was investigated as a separate compo-

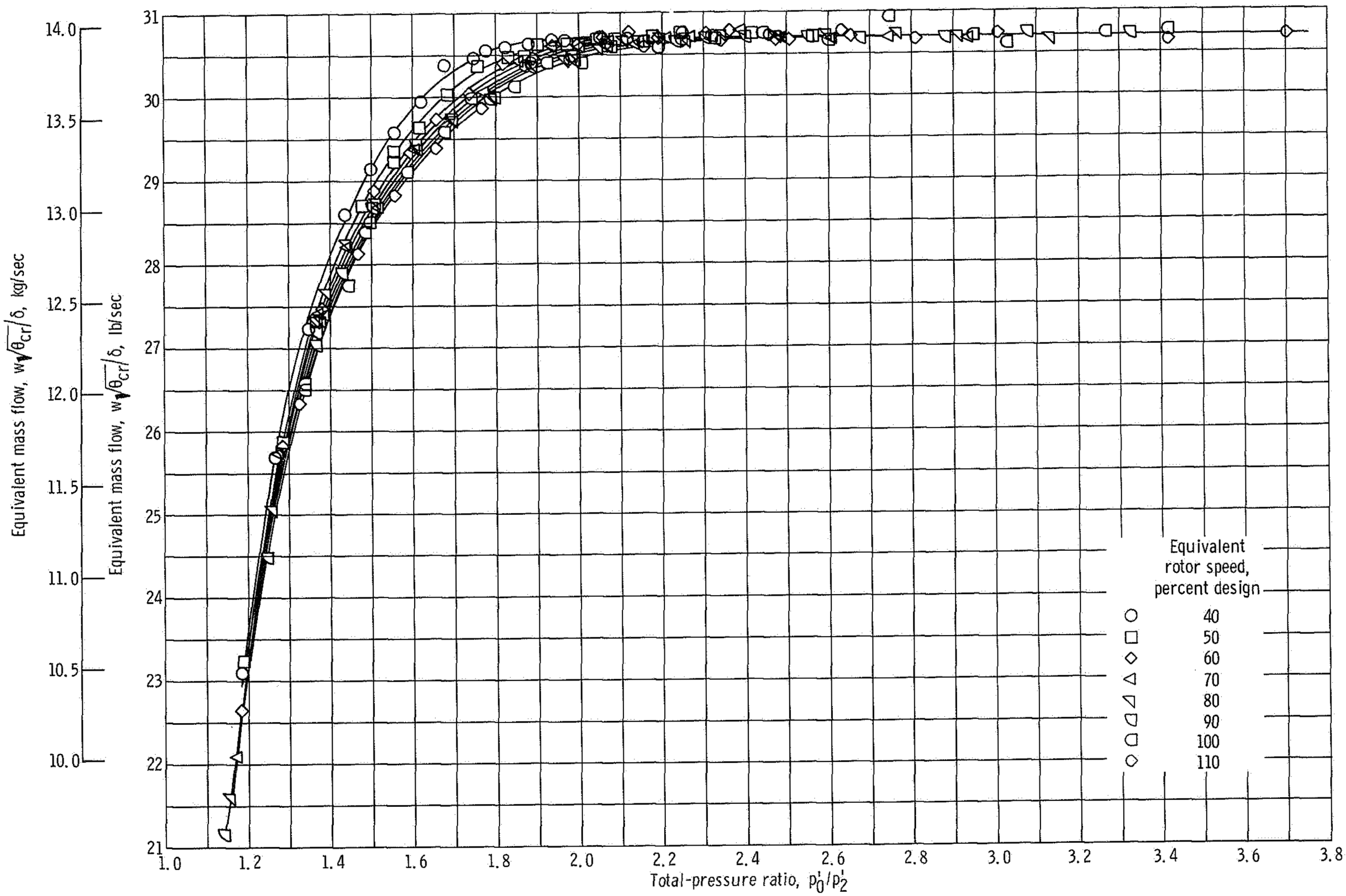


Figure 8. - Variation of equivalent mass flow with total-pressure ratio for various equivalent rotor speeds.

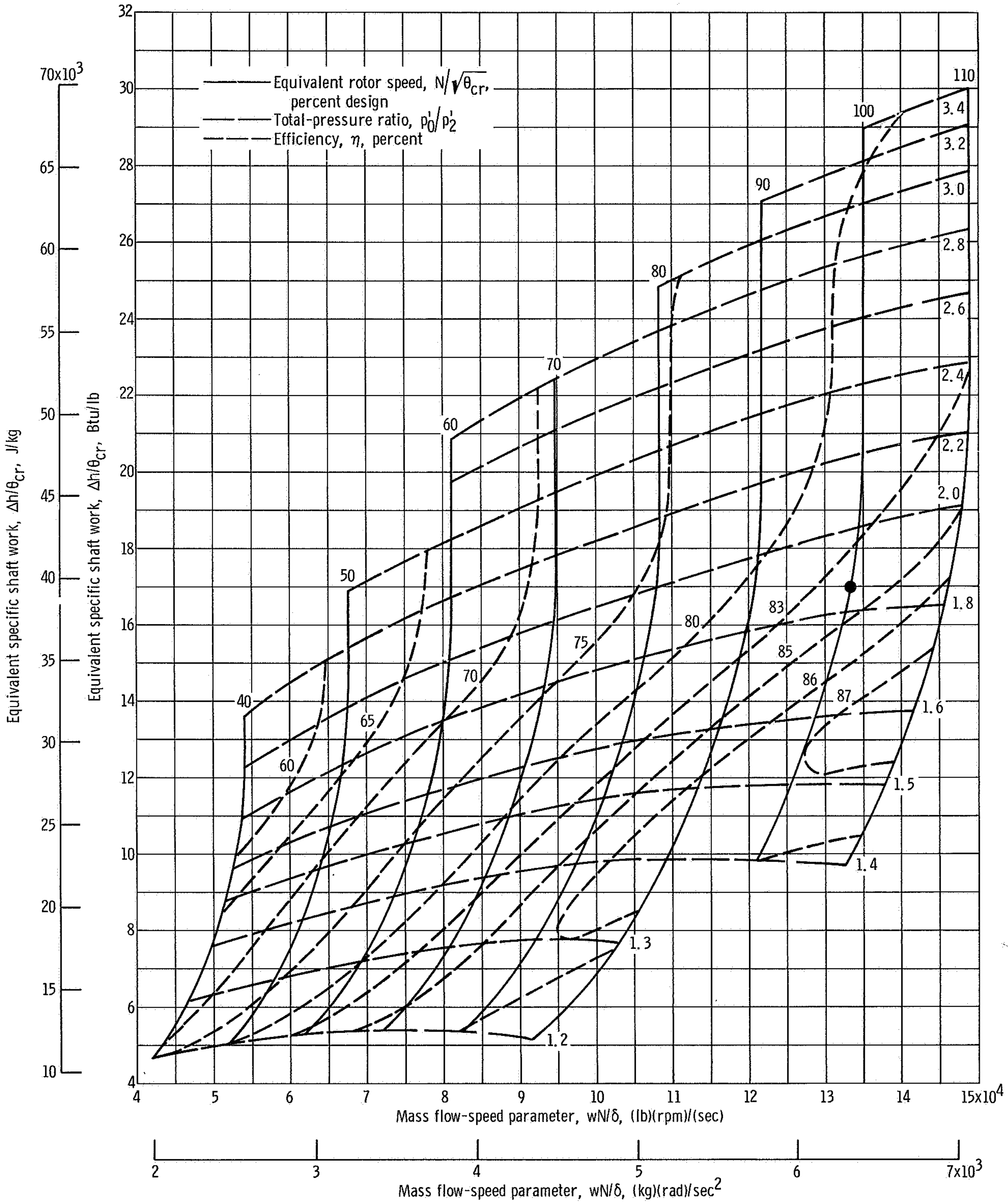
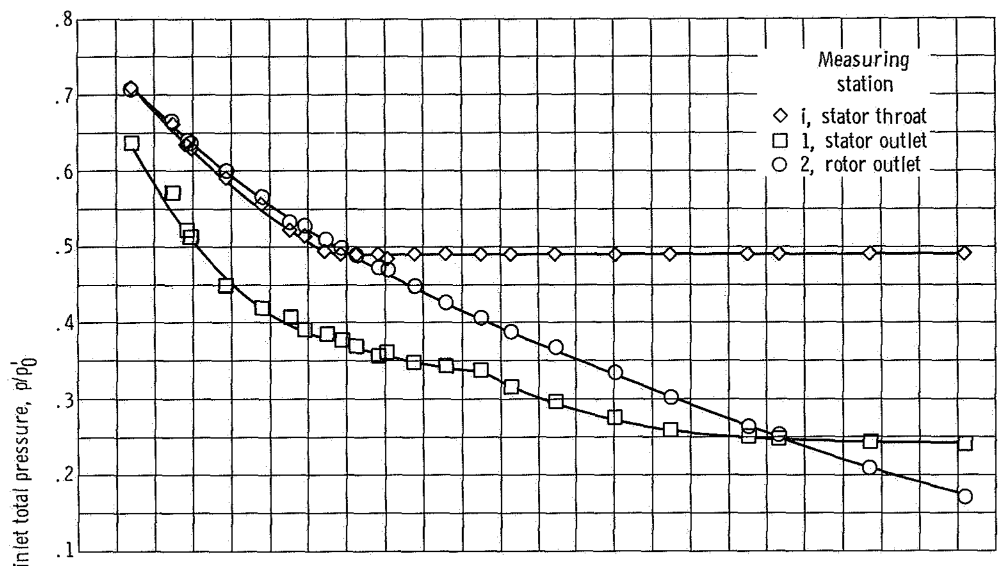
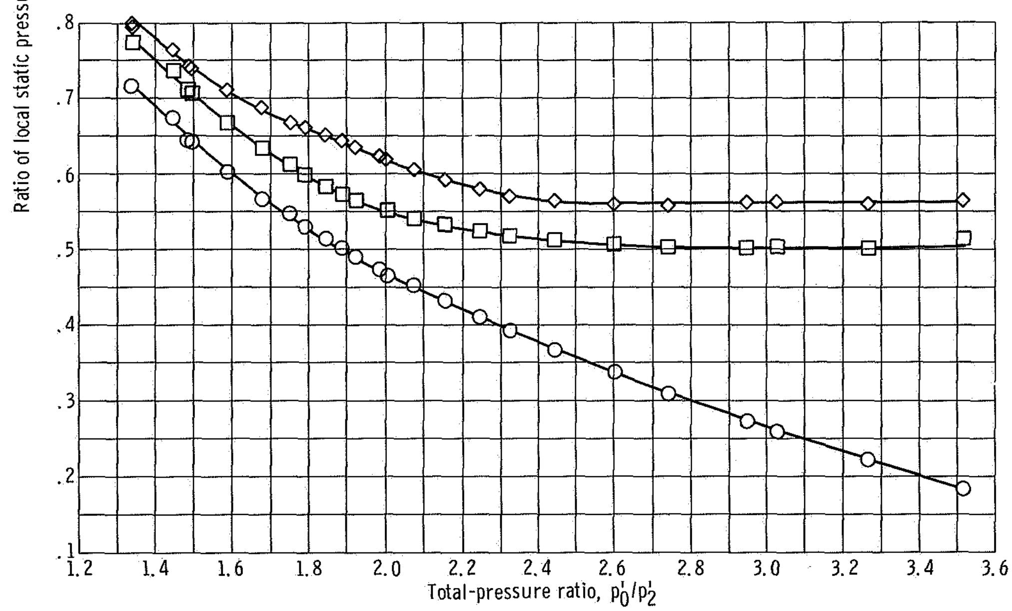


Figure 9. - Turbine performance map.



(a) Hub.



(b) Tip.

Figure 10. - Variation of static pressure through turbine with total-pressure ratio at equivalent design speed.

nent (ref. 5). In addition, figure 10(a) indicates that a static-pressure rise across the rotor occurred at pressure ratios less than 3.04, which indicates negative reaction across the rotor. In contrast, at the tip section (fig. 10(b)), positive reaction across the rotor was always obtained. The significance of the observed hub negative reaction and the supersonic flow condition with attendant shock patterns will be discussed when a comparison is made with corresponding results from the design-turbine and open-turbine investigations (refs. 2 and 4, respectively). The peculiar break in the curve representing stator-outlet conditions at a total-pressure ratio of 2.25, is believed to be attributable to the shock waves affecting the static-pressure readings.

Rotor-outlet flow angle. - The variation of measured average flow angle at the rotor outlet α_2 is presented in figure 11 as a function of total-pressure ratio across the turbine for all speeds investigated. For clarification, positive angles, as measured from axial direction, occur when the exit whirl is in the direction of rotor rotation.

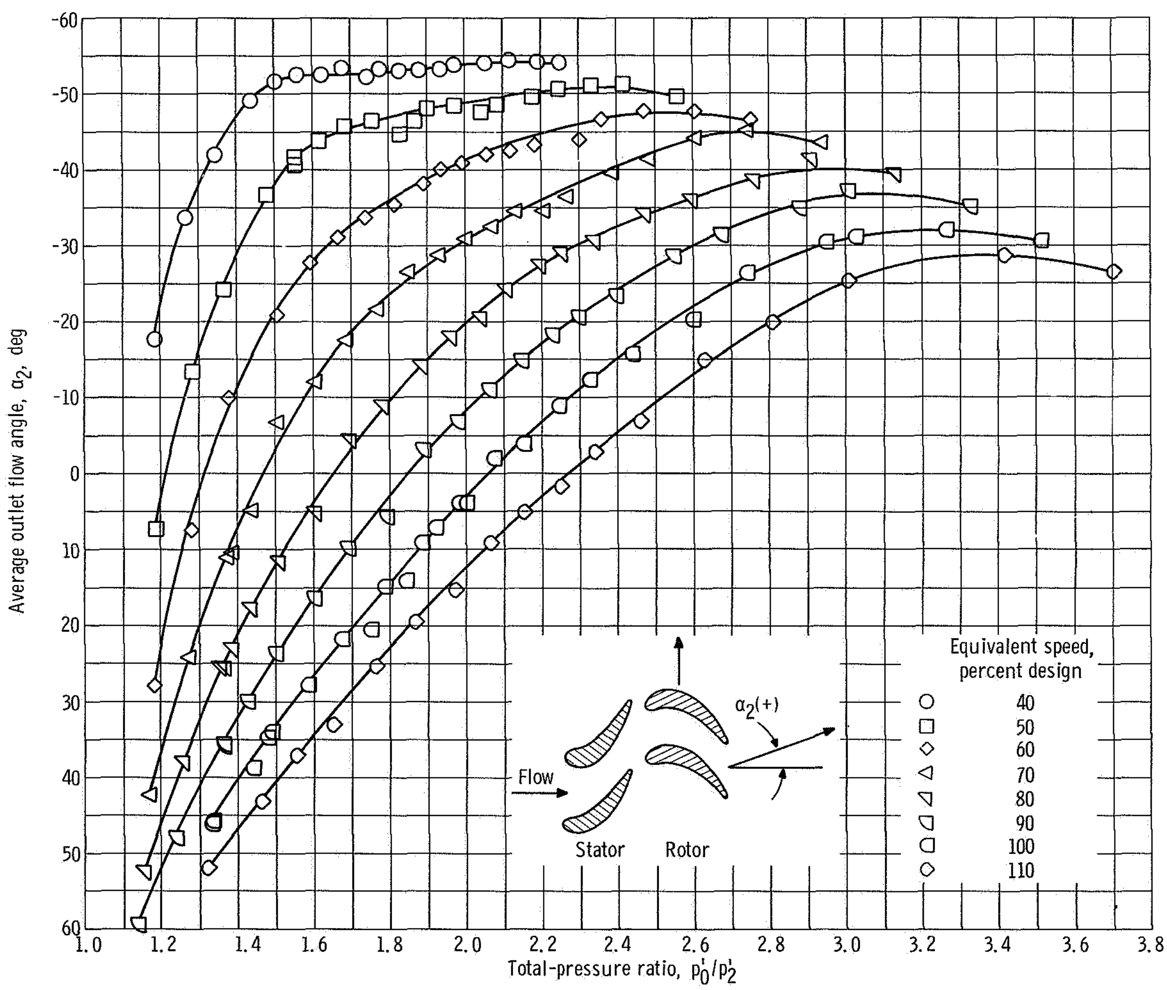


Figure 11. - Variation of outlet flow angle with total-pressure ratio for various rotor speeds.

Figure 11 shows that the rotor-outlet flow angle generally increased with increasing pressure ratio for all speeds. At the 40- and 50-percent speeds, the flow angle was relatively flat over most of the pressure-ratio range investigated. It is interesting to note the wide range of angles measured. Flow angles varied from about -55° to $+60^\circ$. At the total-pressure ratio of 1.860 and for the design speed, where the aforementioned 17.00 Btu per pound (39 752 J/kg) was obtained, the outlet flow angle was 11.0°.

Comparison With Design- and Open-Turbine Performance

Overall performance for the closed turbine is compared with that obtained for the design and open turbines at the design speed in terms of mass flow and efficiency. These parameters are plotted as functions of total-pressure ratios in figures 12 and 13. Trends are representative for all speeds. Subsequent discussion will present the differences in reaction and velocity diagram characteristics for all three turbines when compared at a specific operating point.

Equivalent mass flow. - The mass flows obtained at design speed for the three turbines are presented in figure 12 as functions of total-pressure ratio. The closed-turbine curve is reproduced from figure 8. The curve for the open turbine is from reference 4; that for the design turbine is from reference 2. The rotor choked the flow in the design- and open-turbine investigations. For the closed-stator turbine, however, the stator was

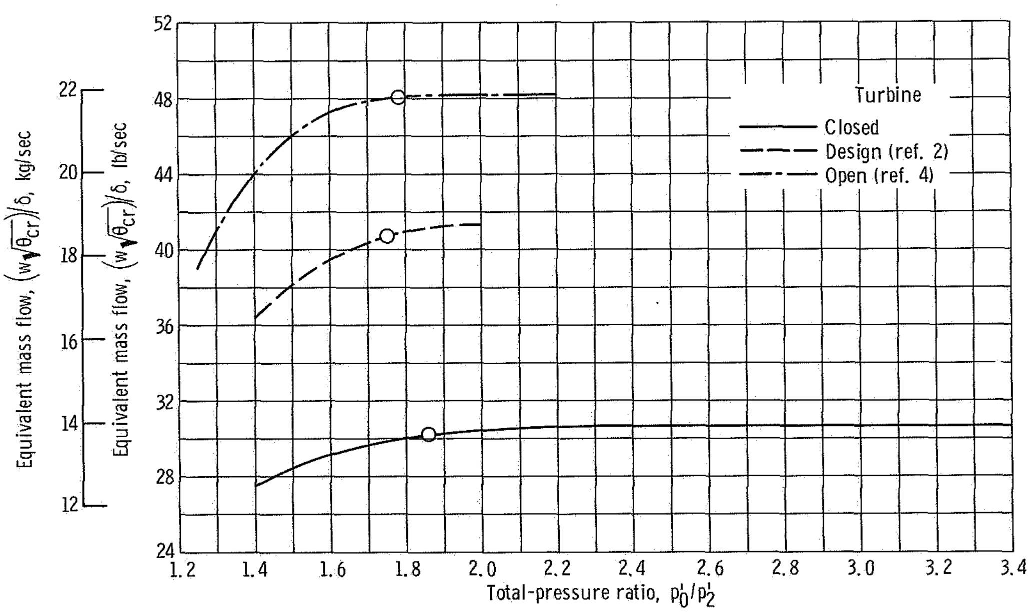


Figure 12. - Variation of equivalent mass flow with total-pressure ratio for three turbines at equivalent design speed.

choked. No direct area-flow comparison can, therefore, be made. However, for the open turbine, where the stator flow area was increased by 30 percent over the design area, only a 16.4-percent increase in flow was observed, and the rotor blade throat area caused this limitation.

The data symbol on each of the curves corresponds to the individual turbine operating point where 17.00 Btu per pound (39 572 J/kg) work output was obtained. It can be noted that all three turbines, when compared at this same turbine operating point, were in the unchoked flow range.

Figure 13 compares the efficiencies at the design speed for all three turbines over a comparable range of total-pressure ratios investigated. It is apparent from the figure that the design turbine yielded the highest efficiencies. Changes in stator area resulted in lower peak efficiencies, and these peak values occurred at lower turbine total-pressure ratios than that for the design turbine. The peak efficiency for the design turbine was 0.923 (ref. 2); for the open turbine, it was 0.909 (ref. 4); for the closed turbine, it was 0.869.

Data symbols are shown on each of the three curves to indicate the condition where 17.00 Btu per pound (39 572 J/kg) was obtained. This point, for the design turbine, was at about the peak obtained efficiency. As the stator area was changed, this point shifted to higher pressure ratios and further from their respective peak efficiencies. Compar-

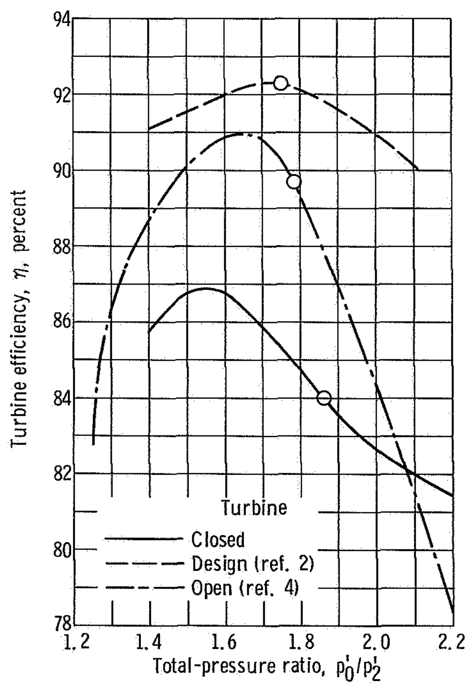


Figure 13. - Variation of turbine efficiency with total-pressure ratio for three turbines at equivalent design speed.

ing the efficiencies at these operating points shows a decrease in efficiency of 0.026 (from 0.923 to 0.897) when the stator area was opened by 30 percent (ref. 4) and a decrease of 0.083 (from 0.923 to 0.840) when the stator area was closed by 30 percent.

The decrease in efficiency for the open turbine (ref. 4) was due mainly to negative incidence on the rotor blade, which occurred as a result of changing the stagger angle toward axial. The increase in mass flow for the open stator caused the interstage pressure to be higher than for the design stator. As a result, the rotor operated at high positive reactions over most of the operating range and was indeed choked at high overall pressure ratios and/or low speeds. In addition, the stator pressure ratios were low enough to maintain subsonic velocity levels and nearly 96-percent stator efficiency in terms of ideal kinetic energy.

The closed turbine, however, operated under a more adverse blade reaction split. The closed-turbine rotor also had incidence, but in this instance it was positive, because of the opposite change in stagger angle. In addition, the low flow through the stator, coupled with the high pressure ratio across the stator (due to the rotor remaining unchoked), resulted in high exit velocities from the stator and into the rotor. In these cases, the stator efficiency was no longer at the same high values as in the subsonic regime, although exact figures cannot be quoted. The high velocity flow was then diffused through the rotor with indications that some flow separation may have occurred at the hub.

The magnitude of the velocities in the turbine and the pressure distribution are discussed in the following sections.

Static-pressure variation. - The static-pressure variation through the three turbines is shown in figure 14. The static pressures were measured at the inner and outer walls of the turbines at the stations indicated. The static-pressure distribution through each turbine was obtained at the design speed and a work output of 17.00 Btu per pound (39 572 J/kg). As stated previously, each turbine was tested with the same rotor. As expected, the expansion through the closed stator was greater than for either the open or the design stators, because the rotor was designed for greater flow. This resulted in the supersonic flow at the hub, the positive incidence at the inlet to the rotor, and the negative reaction across the rotor. These factors contributed to the decreased efficiency for the closed turbine.

The static pressure at the inlet to the turbine (fig. 14) increased with decreasing stator exit area. This was a result of the lower flow (and inlet velocity) as the stator area was reduced.

Velocity diagram comparison. - A mean radius velocity diagram was calculated from the experimental results of the closed turbine in the same manner as described for the design turbine (ref. 2) and the open turbine (ref. 4). In this procedure, the assumption was made that the work output, flow, and stator outlet flow angle at the mean radius

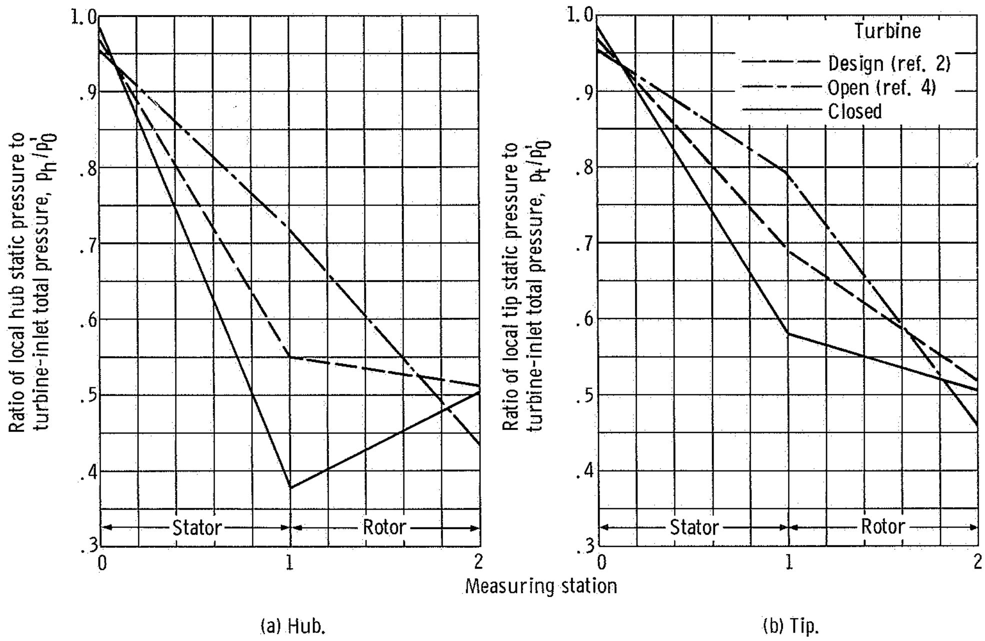


Figure 14. - Comparison of static pressure variation through turbines. Experimental values correspond to equivalent design speed and equivalent work output of 17.00 Btu per pound (39 572 J/kg).

Symbol	Turbine		
	Design	Open	Closed
Velocity, ft/sec (m/sec)			
$V_{u,1}$	747.6 (227.9)	555.4 (169.3)	911.1 (277.7)
$V_{u,2}$	103.6 (31.6)	296.6 (90.4)	58.7 (17.9)
$V_{x,1}$	319.8 (97.5)	341.4 (104.1)	266.0 (81.1)
$V_{x,2}$	381.4 (116.2)	499.4 (152.2)	303.0 (92.4)
V_1	813.1 (247.8)	652.2 (198.8)	948.8 (289.2)
V_2	395.2 (120.5)	582.9 (177.7)	308.7 (94.1)
W_1	404.4 (123.3)	345.5 (105.3)	489.7 (149.3)
W_2	714.0 (217.6)	440.6 (286.7)	535.3 (163.2)
Angle, deg			
α_1	66.84	58.45	73.73
β_1	37.75	9.33	57.1
α_2	-15.2	-30.60	11.0
β_2	-57.71	-57.47	-55.53

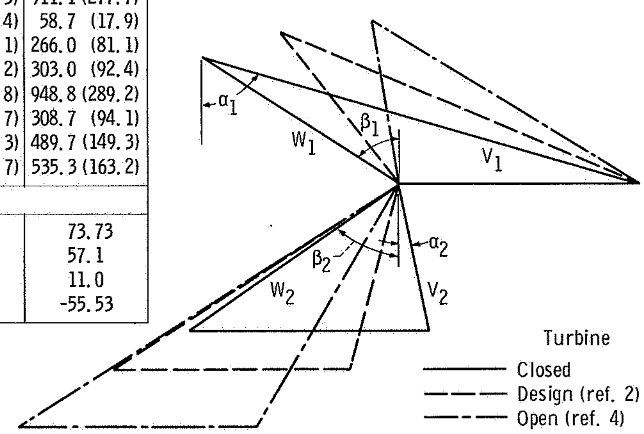


Figure 15. - Comparison of experimentally determined mean-radius velocity diagrams for three turbines. (All velocities in table correspond to turbine-inlet conditions of U. S. standard sea-level air.) Diagrams correspond to equivalent design speed and equivalent specific work output of 17.00 Btu per pound (39 572 J/kg).

represent the average for the blade row. The resultant velocity diagram is shown and compared with those for the two reference turbines in figure 15. Again, the turbine operating point used for comparison is design speed and 17.00 Btu per pound (39 572 J/kg). The table in figure 15 lists the velocities and flow angles to facilitate the comparison.

The stagger angle for the closed turbine stator blading was increased 7.79° from the design turbine in order to reduce the mean section outlet orthogonal by 30 percent. The resultant stator outlet flow angle for the closed stator increased 6.89° from axial, which is close to the geometric angle change. At design speed and work output, the flow from the closed stator was directed into the rotor blade at a relative inlet angle of 57.1°. This corresponds to a positive incidence angle of 19.35°. The relative inlet angle for the open turbine was 9.33°, which corresponds to a negative incidence angle of 28.42°. As expected, both the absolute stator outlet velocity V_1 and the rotor relative inlet velocity W_1 increased as the stator area was reduced.

Comparing the rotor portion of the diagram, figure 15 shows that rotor reaction decreased with decreasing stator exit area. At the mean section, the open turbine had high positive reaction, the design turbine some positive reaction, and the closed turbine almost no reaction, approaching impulse operation. Although it is not evident in figure 15, the closed turbine actually experienced negative reaction at the hub. This is evident from the discussion of the static pressure distribution through the turbine as shown in figure 14. The negative reaction, as well as the small positive reaction, results in an increase in the surface diffusion process and can lead to flow separation if not properly controlled. The 2° decrease in rotor relative outlet angle for the closed turbine indicated that flow separation may have occurred.

Considerable underturning of the flow at the rotor outlet can be noted in figure 15 for the closed turbine. The absolute rotor outlet angle α_2 was 11.0°, which compares with -15.2° for the design turbine and -30.6° for the open turbine.

The lower turbine efficiency in the closed turbine can, therefore, be attributed to three main factors:

(1) High gas velocities at the stator exit

(2) Positive incidence into the rotor

(3) Substantially reduced reaction across the rotor blade with possible separation

A loss estimate on the closed turbine was made, which showed that the stator loss was about 3 percent, the incidence loss about 2 percent, and the rotor loss about 11 percent.

SUMMARY OF RESULTS

A 30-inch (0.762-m) single-stage turbine, designed to exemplify the aerodynamic problems associated with turbines for high-temperature-engine application, is being experimentally investigated to determine the effect of variable stator area on turbine performance. This report presents the experimental results of the turbine having a stator area 70 percent that of design. This area change was effected by reorienting the stagger angle of the stator blades. Results are compared with those previously obtained for both the turbine having design-area stators and the turbine having 130-percent design-area stators. Pertinent results are as follows:

1. Decreasing the stator area 30 percent from design resulted in the stator blade row choking at an equivalent mass flow of 30.71 pounds per second (13.93 kg/sec). The rotor blade row choked in the design- and open-turbine reference investigations.

2. A peak efficiency slightly over 87 percent was obtained at 110 percent equivalent design speed and a total-pressure ratio about 1.6.

3. The peak efficiency obtained at the design speed was 0.869. This compares to 0.909 for the open turbine, and 0.923 for the design turbine.

4. The following was obtained at design speed and at a work output of 17.00 Btu per pound (39 572 J/kg), corresponding to the equivalent design conditions for the reference design turbine:

   a. The efficiency for the closed turbine was 0.840, considerably lower than the value of 0.923 for the design turbine, and lower than 0.897 as obtained for the open turbine.

   b. Decreasing the stator area resulted in increased velocities out of the stator, negative reaction across the rotor hub, and near impulse conditions at the mean-blade height.

   c. The incidence angle relative to the rotor for the closed turbine was about $+19^{\circ}$ and compares to about -28° for the open turbine.

   d. An estimate of the losses through the turbine indicated a 3-percent stator loss, a 2-percent loss due to rotor incidence, and a 11-percent rotor loss.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 8, 1968,
126-15-02-31-22.

REFERENCES

1. Whitney, Warren J.; Szanca, Edward M.; Moffitt, Thomas P.; and Monroe, Daniel E.: Cold-Air Investigation of a Turbine For High-Temperature-Engine Application. I. Turbine Design and Overall Stator Performance. NASA TN D-3751, 1967.

2. Whitney, Warren J.; Szanca, Edward M.; Bider, Bernard; and Monroe, Daniel E.: Cold-Air Investigation of a Turbine For High-Temperature-Engine Application. III. Overall Stage Performance. NASA TN D-4389, 1968.

3. Dugan, J. F., Jr.; Koenig, R. W.; Whitlow, J. B., Jr.; and McAuliffe, T. B.: Power for the Mach 3 SST. Astronautics and Aeronautics, vol. 2, no. 9, Sept. 1964, pp. 44-51.

4. Schum, Harold J.; Moffitt, Thomas P.; and Behning, Frank P.: Effect of Variable Stator Area on Performance of a Single-Stage Turbine Suitable for Air Cooling. III - Turbine Performance with 130-Percent Design Stator Area. NASA TM X-1663, 1968.

5. Behning, Frank P.; Bider, Bernard; and Szanca, Edward M.: Effect of Variable Stator-Area on Performance of a Single-Stage Turbine Suitable for Air Cooling. IV - Stator Overall Performance with 70-Percent Design Area. NASA TM X-1675, 1968.

6. Prust, Herman W., Jr.; Schum, Harold J.; and Behning, Frank P.: Cold-Air Investigation of a Turbine for High-Temperature-Engine Application. II. Detailed Analytical and Experimental Investigation of Stator Performance. NASA TN D-4418, 1968.

7. Moffitt, Thomas P.; Prust, Herman W., Jr.; and Bider, Bernard: Effect of Variable Stator Area on Performance of a Single-Stage Turbine Suitable for Air Cooling. II - Stator Detailed Losses With 130-Percent Design Area. NASA TM X-1635, 1968.

8. Prust, Herman W.; Moffitt, Thomas P.; and Bider, Bernard: Effect of Variable Stator Area on Performance of a Single-Stage Turbine Suitable for Air Cooling. V. Stator Detailed Losses With 70-Percent Design Area. NASA TM X-1696, 1968.

NASA-Langley, 1968 — 1 E-4586

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